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Radar Cross Section Reduction of Naval Ships.

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31 August 1987
Technical Report
ONT Fellow: YURI JOHN STOYANOV

During my one year appointment Sep. 1, 1986- Aug. 31, 1987 I worked in the Ship Electromagnetic Signature Department, Observables Technology Division of the David Taylor Naval Ship Research and Development Center.

Work during this appointment has resulted in three technical reports. Technical Report No. 1 entitled "Radar Cross Section Calculations of Metallic Box with Cavity" covers theoretical aspects of the problem. Technical report No. 2 is concerned with numerical calculations of the radar cross section of a metallic box with cavity and its implementation in a ship radar cross section computer model. In technical report No. 3 a great deal of effort has been expended in order to find the "proper" theoretical statistical distribution or distributions which will adequately describe the variations in amplitude of radar return from a complex target such as a naval ship.

Technical report No. 1 has been drafted and will be published in the near future. The work on technical report No. 2 and 3 still continues and will be published after its completion.

Because the ONT Postdoctoral contract expired prior to the completion of this work a summary of results achieved during contract period will be provided in place of the above two mentioned reports. However after completion of these reports they will be available to the agency upon request.

Beginning in September 1, I will continue to work on the project as a DTNSRDC employee.



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RADAR CROSS SECTION REDUCTION OF NAVAL SHIPS.

ABSTRACT

Until recently, attempts to measure and reduce the radar cross section (RCS) of ships have not been given high priority because it was felt that a meaningful reduction would not be practical. However, advances in computational modeling, as well as British Navy combat experiences at the Falkland Islands and other military developments, strongly indicated a growing necessity to disguise the unique characteristics of combatant ships, to minimize their RCS and reduce their detectability, and to employ electronic countermeasures of reasonable power levels, in order to increase their survivability and thereby allow them to successfully accomplish their missions.

Physical mechanisms and theoretical foundation underlying different methods of minimizing the radar cross section of Navy ships are examined for the purpose of reducing surface ship detectability. Also discussed are the statistical description of radar returns from naval ships and the RCS analysis of specific bodies of interest to the Observables Technology Division.

ADMINISTRATIVE INFORMATION

This project was supported by the ONT/ASEE Postdoctoral Fellowship Program and by the DTNSRDC Independent Exploratory Development Program, sponsored by the Office of Chief of Naval Research, Director of Navy Laboratory, OCNR 300 and administered by the Research Coordinator, DTNSRDC 012.3 under program Element 61153N, Task Area 2R-000-01-01 under DTNSRDC Work Unit 1-2930-021-10.

Subject and purpose.

During my ONT appointment period I was involved in writing an IR PROPOSAL FOR FY87, entitled : Radar Cross Section Reduction Concepts.

The principal investigator of this research proposal is Dr. Clifford R. Schumacher, Code 1411.

As an associate investigator of this proposal, I prepared and later submitted for approval a research plan which consists of two parts:

- 1) Geometrical Theory of Diffraction (GTD) effects, concerning prioritization of contributions to the Radar Cross Section (RCS) of Navy ships.
- 2) Interaction of Radar Absorbing Materials (RAM) with electromagnetic radiation, concerning internal waves in dielectric coatings and their re-radiation. However, due to the department priorities, this part of the proposal is replaced by: Statistical description of radar returns from naval ships.

The objective of this research work is to examine the physical mechanisms and theoretical foundation underlying various methods of minimizing the RCS of Navy ships, to reduce surface ship detectability and vulnerability to enemy weapons and thereby increase ship survivability.

The proposed approach to meeting this objective is based primarily on the fact that existing computer models do not take into account all scattering phenomena and concentrate instead on specular reflection, with a limited treatment of diffraction effects. This leads to various discrepancies between calculated RCS values and experimental results. By taking into account more scattering mechanisms, including interference and diffraction, polarization effects, and surface (i.e. creeping and traveling) wave phenomena, their prioritization based on individual contributions to the ship RCS may lead to a better agreement between predicted and experimental results. These studies may also serve as an effective tool in reducing computer run time of RCS calculations, which are often quite lengthy, by determining when diffraction effects may be safely ignored.

Introduction.

One vital fact can be recognized: while air and surface defense of navy vehicles has been greatly reinforced by radar, it is also becoming entirely dependent on it, for two reasons. One is that speeds and altitudes of aircraft and missiles have outrun the capability of the human eye; the other is that electronic aids developed in parallel with radar make it possible for the attacker to strike naval ships accurately at night or in bad weather.

Unlike any previous weapon, enemy radar does not need to be destroyed or physically damaged to be rendered ineffective. If its signals can be counterfeited, distorted, minimized, or muffled with electronic noise, it can be neutralized just as effectively, often from a considerable distance.

A radar system searches a volume of space for targets by scanning it rapidly with a controlled beam of energy. When this beam encounters a target, the effect is the same as when a flashlight beam shines on model ship: the target becomes visible.

Actually, from a physics point of view, radar energy acts in a somewhat different way, although the basic phenomena are the same.

In order to clarify this point of view, without going into details, the concept of scattering centers can be introduced.

Any metallic target seen by a radar looks very different from the same target as seen by the eye with natural optical illumination. There are two reasons for this:

1. The surface of targets in general are rough, compared to the wavelength of light so that light is scattered in all directions, whereas the same surface is smooth compared to the radar wavelength resulting in only specular reflection, diffraction at surface discontinuities, and other RCS effects mentioned above.

Most metallic surfaces are smooth to radar, and yield highly concentrated specular reflection. This very efficient reflection accounts for the extreme range at which radar can detect targets, particularly Navy ships. With respect to other RCS effects, it is necessary to note that a radar beam is an electromagnetic field, and it generates a sympathetic field in any conductive object on which it impinges; i.e., as well as being a target, the object becomes an antenna. Radar waves can "creep" around a curved body and emerge on the other side. Sometimes, these augment the direct reflection; at other times, they may cancel it out. Waves may also creep into a cavity, and may resonate there.

Also, radar waves are subject to diffraction. Whenever a radar beam is reflected, whether by its transmitted antenna or by a target, part of the beam is retransmitted as side lobes, simply because the antenna's natural tendency is to radiate in all directions. The side lobes flank the main beam; they are not as powerful as the main beam, or its specular reflection, but often are an important factor.

2. Illumination with a radar is in general with parallel wavefronts while natural optical illumination is in general diffuse.

A well known object, the surface of which is smooth compared to optical waves, is ordinary water tap. Its photograph is similar to that observed when the radar sees a metallic target such as naval ship. It does not see the whole target, it only can see the scattering centers on the ship.

Two observations apply to these phenomena: (a) one is that the size of an object is only one of the factors that determines how much energy is reflected back toward a radar, and sometimes is not a particularly important one, and (b) specular reflection of the main radar lobe is by far the brightest object in the radar's field of view.

The most important point to be made about RCS is that a small, efficient reflector - such as a flat plate, normal to the radar beam - can reflect as much energy as a considerably larger sphere, and thus have a large RCS.

For RCS analysis it is appropriate therefore to replace the radar targets by their scattering centers.

Observation of radar targets with ultra-high-resolution radar produces returns in accord with the predictions of scattering-center theory. The scattering-center concept is highly useful for analysis of radar scattering because consideration of a small number of scattering centers is sufficient to permit estimation of the scattering from many types of relatively complex radar targets.

Scattering of radar waves by ships.
(Ship radar cross section concept)

Modern radar scattering analysis dates from the introduction, over 30 years ago, of the geometrical theory of diffraction (GTD) by J.B. Keller. This approach, still under active development, is based upon asymptotic expansion techniques permitting the computation of the contributions from individual scattering centers and relies upon the essentially local nature of the scattering phenomenon.

Interpretation of the most important principles of the Geometrical Theory of Diffraction (GTD):

In the high frequency region ($\lambda \ll L$), collective interactions are very small, so that a body can be treated as a collection of independent scattering centers, hence detailed geometries are very important.

High frequency techniques include:

1. Geometrical optics (GO), which is the high frequency limit of zero wavelength in which the scattering phenomena is treated by classical ray tracing.
2. Physical optics (PO), which is similar to the integral equation description since it is based on source currents.
3. Geometric theory of diffraction (GTD), which extends the usefulness of GO to regions where diffracted fields are important, such as shadow areas.
4. Physical theory of diffraction (PTD), which explicitly removes the physical-optics surface effects from GTD.
5. Method of equivalent currents (MEC), which represents edge-diffracted fields in terms of fictitious filamentary source currents.

By comparing the GTD procedure with other techniques, mentioned above, we may refine interpretation of the GTD principles.

The physical optics (PO) formalism retains some concepts of low-frequency scattering techniques i.e., the concept of surface currents is retained and thereby PO is limited, because it does not account for edge or surface wave scattering.

When λ is small enough ($\lambda \rightarrow 0$) the energy flow is along the ray paths and when $\lambda \ll L$, optic principles govern the behavior of the scattered field, hence GO and GTD approaches are better suited for high frequency.

The principal ingredients of GO are:

1. Ray paths
2. Ray spreading
3. Reflection coefficients

GTD is the extension of GO to include the propagation of energy into shadow regions, namely, diffracted rays, hence adds the following to the list:

4. Diffracted ray paths, including surface rays
5. Diffraction coefficients.

GO fails when we must consider fields scattered from edges, tips, corners, shadow regions. This is because E&H fields are no longer transverse to the direction of propagation in the vicinity of discontinuities.

GTD is the procedure which takes into account the above effects.

Prioritization of RCS effects.

For a complex body such as naval ship, there are many significant effects which may contribute to the RCS:

1. Specular scattering.
2. Diffractive effects:
 - a) diffractive scattering from surface discontinuities such as edges, corners, and tips;
 - b) scattering from surface derivative discontinuities;
 - c) creeping wave or shadow boundary scattering;
 - d) traveling wave scattering;
 - e) scattering from curved surfaces (convex, concave);
 - f) cavity scattering;
 - h) polarization effects.
3. Effects due to the interaction between scatterers of a complex body, such as a ship.
4. Effects due to the interaction between sea surface and the ship, such as multipath or other multiple bounces.

The contribution of each of the above effects to the total ship RCS is not constant & may depend on the following factors:

1. Target configuration
2. Frequency
3. Incident wave polarization
4. Polarization of the receiver, and
5. Angular orientation of the target with respect to the incident field.

It is important to realize that for a complex body, such as a naval ship, there are many significant contributors to the RCS, and that, especially as we succeed in damping the specular contribution, the next largest contributions may come from more than one source.

In discussing the contributions of these components of the RCS, we can use a fixed wavelength and let the aspect vary, or we can consider a fixed aspect and let the wavelength vary. Let us use the latter approach and concentrate on the bow-on aspect and its vicinity.

Three RCS regimes characterize the relationship between the wavelength & scatterer size L . They are:

1. Rayleigh region ($L \ll \lambda$), ($0.01 \leq L/\lambda \leq 1.0$)
2. Resonance region ($L \sim \lambda$), ($0.1 \leq L/\lambda \leq 10.0$)
3. Optics region ($L \gg \lambda$), ($1.0 \leq L/\lambda \leq 100.$)

The ship may be treated as a collection of simple isolated scatterers. As such, the high frequency size requirements (that the body be at least several wavelength in size ($L \gg \lambda$)) must be applied to these simple shapes, and not necessarily to the overall ship target.

a) Rayleigh Scattering ($L \ll \lambda$)

Rayleigh scattering occurs at low frequencies, when we can assume that there is essentially no phase variation of the incident wave over the scattering body.

For Rayleigh scattering, the entire body participates in the scattering process. Details of the shape are not important and, therefore, only a basic or crude geometric description is required. However, surface area and volume of the scatterer are important.

In this regime, specular reflection contributions are the main constituent of the total ship RCS. Polarization (\parallel or \perp) may significantly change the total RCS, since the strength of the induced dipole moment is a function of the size & orientation of the body relative to the vector direction of the incident field.

In the Rayleigh region, there is little variation in either the amplitude or phase of the incident field over the body length, however there is very strong dependence on the frequency. ($\sigma \propto \omega^4$ or k^4)

b) Resonance Scattering ($L \approx \lambda$)

In this regime, every part of the scatterer affects every other part. Therefore, collective interactions are very important. In addition, the overall geometry is important, even if very small details are not.

Contributions from specular reflection still dominate, but their share of the overall RCS has decreased, while the diffractive contributions increase significantly in comparison to the low frequency regime.

In the resonance regime, the scattered field may be found from the computed surface current distribution, hence surface patch models such as those used by NRL and Georgia Tech are applicable.

c) Optics Region ($L \gg \lambda$)

The optics region occurs at high frequencies, where collective interactions are very small, so that a body can be treated as a collection of independent scattering centers, and the approximations of Physical or Geometrical Optics may be used. Boundary integral equation methods are limited to bodies not much greater than 10λ in size.

Detailed geometries now become important in the scattering process.

In addition, diffractive effects are now very important. The GTD (Geometrical Theory of Diffraction) approach can be used in calculating RCS, since it extends the usefulness of Geometrical Optics to regions where diffractive fields are important, such as shadow areas.

Important contributions to the RCS now come from edge diffraction.

GTD is the procedure which can take such effects as scattering from edges, tips, corners, tangent points or shadow regions, curvature, & multiply diffracted rays into account.

The RCS effects, listed above, can be prioritized based on the hierarchy of scattering shapes, as shown in Table 1. As was already mentioned, the RCS of the ship depends on the operation of several kinds of mechanisms, some of them simple, but many of them complex. These mechanisms can be categorized according to their strength, which in turn is closely related to their frequency dependence F and their dimension L .

The "largest" (with respect to RCS contribution) scatterers in this hierarchy are the corner reflectors. The large echo is due to the mutual perpendicularity of the two or three faces comprising the corners. Rays that impinge on such structures are reflected back in a wide range of viewing angles. The RCS of a corner rises with the square of the frequency of the incident wave and also with L .

The next three simple shapes are flat plate, cylinder and sphere. In these three cases, the body is oriented for a specular returns, e.g., there is a point on the surface where the outward normal points directly back to the radar.

For a flat plate, the entire surface is specular, while for a cylinder, it is a bright line running from one end of the cylinder to the other. For the sphere (doubly curved surface) there is a specular point. For a flat plate, cylinder and sphere the dependence of their contributions on the frequency of the incident wave is F^2 , F^1 , F^0 , respectively, while dependence on the body size L ranges from L^4 for a flat plate to L^2 for the sphere.

When one of the radii of surface curvature goes to zero, an edge is created and another triad: straight edge, curved edge and apex, can be listed in the hierarchy of RCS.

Finally, there is a collection of RCS effects whose returns are very small for nonspecular aspect. These all involve discontinuities of curvature: in the surface along a straight line for normal incidence, of a curved edge, and discontinuity of curvature along an edge, respectively.

The RCS of a complex body such as a naval ship contains several dozen significant scattering centers and a great deal of less significant scatterers, the net RCS will exhibit dependence on aspect angle due to the mutual interference as the various contributions go in and out of phase with each other. The large RCS of naval ships is also due in part to the multipath environment provided by the sea surface. In addition, many topside surfaces are vertical, thereby forming efficient dihedral corner reflectors with the mean sea surface. The significant scatterers on a ship will depend on the range between the radar and the ship because of the earth curvature and other effects. For all except broadside incidence, the hull may be replaced by the superstructure and masts as dominant scatterers. There is also scattering from assorted fixtures and equipment located topside of the ship. Consequently, the first steps in the reduction of the RCS of naval ship will include reduction of RCS of the superstructure and masts.

Table 1

Hierarchy of scattering shapes.

1. Corner reflectors	
a) square trihedral	$RCS \propto F^2 \text{ \& } L^4$
b) right dihedral	$RCS \propto F^2 \text{ \& } L^4$
2. Flat plate	$RCS \propto F^2 \text{ \& } L^4$
3. Cylinder	$RCS \propto F^1 \text{ \& } L^3$
4. Sphere	$RCS \propto F^0 \text{ \& } L^2$
5. Straight edge (normal incidence)	$RCS \propto F^0 \text{ \& } L^2$
6. Curved edge	$RCS \propto F^{-1} \text{ \& } L^0$
7. Apex	$RCS \propto F^{-2} \text{ \& } L^0$
8. a) Discontinuity of curvature along a straight line normal incidence.	$RCS \propto F^{-2} \text{ \& } L^0$
b) Discontinuity of curvature of a curved edge	$RCS \propto F^{-3} \text{ \& } L^{-1}$
c) Discontinuity of curvature along an edge	$RCS \propto F^{-4} \text{ \& } L^{-2}$

At least eight basic types of electromagnetic scattering can be considered, and each of them in turn can take various forms. These types of electromagnetic scattering can be listed according to their significance in radar scattering from naval ships: (1) specular reflection; (2) diffuse scattering, including multipath bounces from sea surface; (3) sharp discontinuities in metallic surfaces; (4) reentrant-cavity scattering; (5) creeping waves (shadow boundary scattering); (6) traveling waves; (7) internal reflection and refraction related to dielectric layers; and (8) polarization type dependence.

Specular reflection, when it occurs, usually produces a larger amount of scattering than other forms. Specular scattering arises when a target surface (smooth relative to the illuminating wavelength) has a normal in the same direction as the radar. For most bodies specular reflection is strongly dependent on orientation as well as on shape; for many radar targets specular reflections occur only for very limited ranges of aspect angles. There are three principal types of specular reflection: from doubly curved surfaces, singly curved surfaces, and flat surfaces. All these types of reflection share one feature: they do not depolarize linearly polarized waves, although they will reverse the sense of circular polarization for backscattering. Because there is little if any depolarization of the backscattering field, the physical optics approximation should give good results.

Diffuse scattering is produced when the surface is rough with a height variation smaller than a wavelength. In contrast to specular scattering, diffuse scattering is not generally so sensitive to aspect angle. For many complex targets such as aircraft or naval ships, rough-surface scattering from structures may not be significant at conventional radar frequencies, although it may become significant for millimeter waves and is certainly important at laser frequencies. Note that rough-surface effects in the sea environment may become significant for more-conventional radar frequencies.

Internal reflection and refraction are important contributors to radar returns from coatings and dielectric bodies. Their significance may increase soon, mostly because of the growing use of radar absorbing materials (RAM) for the purpose of reducing the RCS of Navy vehicles. For naval ships, as well as for many other types of radar targets, one of the most important sources of backscattered energy is sharp discontinuities in metallic surfaces. Such discontinuities give rise to scattering contributions that tend to be much smaller than those produced by specular reflection but are present over a wide range of aspect angles.

Finally, there are diffraction effects. For many radar targets, diffraction effects are the entire source of the radar return at most aspect angles. Furthermore, in some forms of radar systems, a nonspecular return may occur at a time different from that of the specular return so that it is a significant part of the output of the radar. Sharp edges are common contributors to the radar return from ships.

Creeping waves and reentrant-cavity scattering can also be important. Two common types of reentrant or reflex scatterers are jet-engine ducts and corner reflectors.

Scattering from corner reflectors can be approximated quite well by assuming optical reflections from the flat surfaces and by examining carefully the changes in polarization produced by the multiple reflections. In addition to being diffracted from surface discontinuities on conducting bodies, rays incident on smoothly curved surfaces can propagate along such surfaces. Such a creeping wave radiates continuously as it propagates, continually emitting rays at a rate depending upon the local radius of curvature.

These different types of electromagnetic scattering on naval ships provide RCS contributions which are not constant and may depend on ship configuration, radar frequency, polarization of incident wave, and angular orientation of the ship with respect to the radar.

The approach to the ship RCS estimation problem outlined above involves the assumption that the radar is either of the continuous wave (CW) type or that the pulse length exceeds the length of the ship so that all scattering centers contribute in a given pulse. If this should not be the case, i.e. for a very short pulse, the ship RCS values might be dictated by the individual scattering centers with the RCS value of the largest contributor being the measure of interest.

Radar cross section measurements of naval ships present a very complex problem not only because of their geometry but also because of the nonuniform illumination of their area resulting from the interference pattern formed by reflections from the sea surface. The echoes from naval vessels usually fluctuate rapidly over a wide intensity range. Because measurement of such echoes is very difficult, the interpretation of ship radar cross section encounters difficulties from the practical standpoint.

In addition to ship RCS contributions from the ship itself and multiple reflections involving ship and sea, the movement of the ship through the water creates a wake which could be a critical and important contributor to the received signal. Even for small ships moving at high speed, the created wake may have large dimensions, such as height and length. It is clear that, with such perturbations of the sea surface, radar scattering from the wake might provide a signal strong enough for detection.

An examination of some of the radar literature reveals that electromagnetic wave propagation over water exhibits variable attenuation; this means that calculation of ship radar cross sections from measurements of radar parameters and range alone leaves errors in excess of several dB, unless there is a precise knowledge of the actual attenuation over the water path at the time and place the measurement took place. Scattering from the reflecting surface of the sea and the resultant multipath interference is an important contributor to ship RCS.

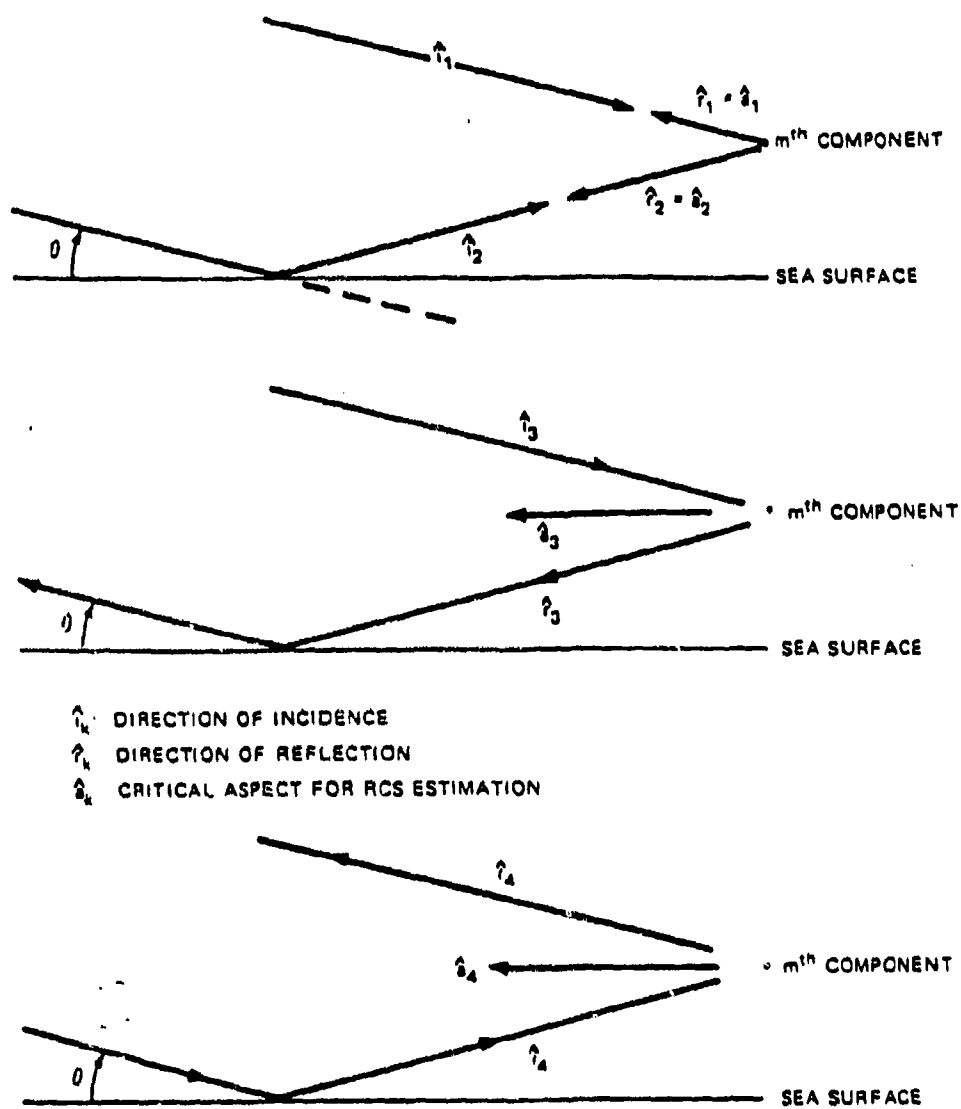
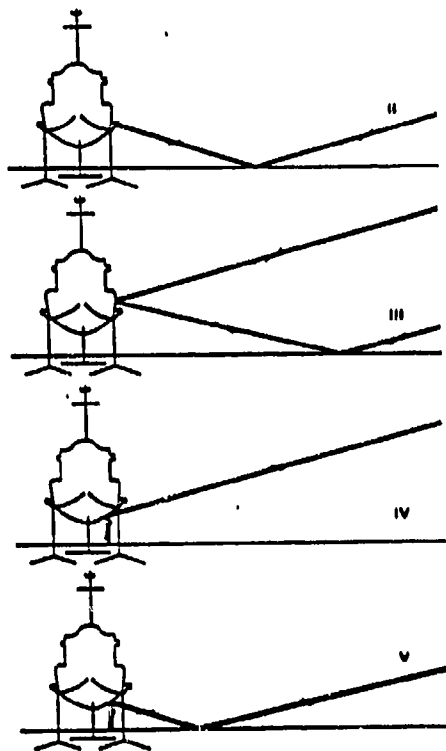


Fig. 1 CRITICAL RAY PATHS FOR A SHIP ON THE SEA, RCS ANALYSIS

Fig. 2 Energy paths.



The most important ways each scattering component of the ship contributes to the ship RCS involve four distinct paths, which are shown in Figure 1. These four possible paths are:

1. A direct reflection from the ship component, i.e., without any interaction with the sea surface,
2. A ray path going from sea-to-component-to-sea back to radar,
3. A ray path going from component-to-sea-to-radar,
4. A ray path going from sea-to-component-to-radar.

The first ray path involves a direct free-space type of return at the elevation angle θ . The second ray path involves two "bounces" from the sea surface and a reflection from the component at an equivalent free-space elevation angle $-\theta$. In contrast to these two paths, the third and fourth ray paths should yield returns that are "in phase" and involve only one bounce from the sea surface. Accordingly, it is most likely, at least on the basis of the study of the bistatic RCS, that the reflection from the component in these cases is similar to that of the $\theta = 0$ free-space case.

For almost all ships, the contributions of type 4 and other less important paths not listed above, but are shown in Figure 2, such as a ray path that reflects from component-to-sea-to-component-to-sea-to-radar are very small and may be neglected in comparison with say, the type 3 return.

It follows from the above discussion that elevation angle 0 is an important factor that affects the propagation path and therefore the RCS data. Thus, when the radar range is near the horizon, the horizon effect such as shadowing of the target ship by the earth's curvature becomes important. The problem is how to incorporate these propagation effects into the definition of cross section.

The choice is complicated by the fact that at least three different propagation conditions can be defined in terms of the geometrical relationships between the radar antenna height, the target ship height, and the radar-to-ship distance in relation to the earth's curvature. Note that, for each of these conditions, the cross-section problem is subject to different effects. There are the following three conditions:

- a) The near zone, i.e. when the radar antenna height and target ship distance are such that the entire ship hull is visible from the radar, and interference between direct and sea reflected rays results in a pattern of maxima and minima of field strength incident on the target ship; and
- b) the two far zone conditions, i.e when the target distance is such that the entire hull is still visible, but the highest point of the ship is appreciably below the first maxima of the sea-reflection interference pattern, and
- c) when the target is such that part of the ship is in the shadow of the earth's curvature, and only the upper part is illuminated by the radar while the other part of the ship is below the horizon.

It is appropriate to mention that RCS loses its meaning if the target is not uniformly illuminated. Such can be the case, for example, if waves reaching the target via two or more paths combine to produce an interference pattern at the target. Thus, for the first two conditions (cases a) and b)) the cross section is definable, whereas for the third condition the cross section is a function of range. Therefore, as all this suggests, the problem of ship-target cross section definition has not been completely resolved except for the near-zone case. Because the maximum detection range of ships usually occurs in the far zone or even in the horizon-shadow region, when the radar is either on the ground or on another ship, this situation is far from satisfactory.

One of the possible approaches used is to find the solution by using approximate results, where the cross section measured for the near zone may be used for estimating the pattern propagation effect for the far zone.

For detection of ships from airborne or space-borne radars, the problem simplifies since here the near-zone propagation condition usually applies, although some additional specific effects occur. Note that from land or ship-based radar, particularly in the near zone, it is reasonable to assume the sea reflection to be that from a flat perfect reflector since surface roughness is then often insignificant at the small grazing angles involved. This is in contrast to high-altitude radars where grazing angles are steeper, and sea surface roughness may be significant. In turn, this means that ship cross sections measured for one sea state may differ from those measured for a smoother or rougher sea.

For airborne or space-borne radar, in addition to this effect there is also a so called "corner reflector" effect, i.e., when the hull of the ship is approximately vertical so that the reflecting sea surface and the hull form a two-plate corner reflector. This causes a relatively large cross section when the radar viewing angle is approximately broadside to the ship. For such a case, the sea roughness has a great effect, as does also the rolling of the ship, which destroys the required perpendicularity of the two reflecting surfaces. Naturally, rough seas and ship rolling tend to occur together.

Note that, when a slight rolling occurs in relatively smooth seas, the destruction of the corner-reflector effect is usually larger and significant fluctuations of the echo signal strength take place near the broadside aspect.

As with high-altitude radar detection of ships discussed above, ground radar also is affected by ship roll. For this case, ship roll produces similar large fluctuations in RCS for broadside aspect as a result of the flat-plate reflection effect.

It is apparent, therefore, that echo patterns from naval ships will exhibit complexity in terms of variation in RCS with relatively small changes in target aspect with respect to the radar line-of-sight. This in turn complicates the interpretation of measurements of ship radar cross section.

However, for the purpose of simplifying the solution, it is important to distinguish between two aspects of the problem. It is still true that, for every possible type of incident radiation and configuration of the elements of a complex target such as naval ship, a unique scattering pattern exists. From this pattern an effective value of ship RCS could, in principle, be determined uniquely for any particular direction. When a naval ship is in motion, however, ship RCS varies so rapidly and over such a wide range that the final outcome of any measurement depends markedly on the observer and his instruments.

Because of the need for some means of describing complex targets, certain averages evolved to preserve the concept of the RCS of complex targets, such as a naval ship.

Several different means of defining a ship RCS may be appropriate to consider and select, depending on the target ship and its interaction with the radar. A median RCS value is often used: this value is calculated over a range of target ship aspect angles where the median value represents the fifty percent point of the amplitude cumulative probability distribution function of RCS values. For a land based radar, the range of target aspect might reasonably be limited to ± 10 degrees from head-on orientation.

Note that ship RCS fluctuations are the results of constructive and destructive summation of energy reflected from individual scattering centers, because a ship RCS can be considered as a collection of many scattering centers. These summations are a function of target ship aspect due to spatial arrangements, orientation, and individual reflectivity of these centers.

Radar return from a typical sea target undergoes extremely large variations from moment to moment. These variations arise from several causes, but the most important is the incessant motion of the target, which is continually changing its aspect and thereby the relative phases between scattering elements. As aspect changes, the three-dimensional cross-section pattern of the target is swept past the line of sight in a complex and irregular manner. For large sea targets this pattern has an extremely fine lobe structure so that even a moderate angular motion can produce amplitude scintillations having relatively high frequency, as well as large dynamic ranges.

Aside from aspect changes, amplitude fluctuations can also arise from changes in the effective size of the target. For example, changes in the exposed height of a ship hull, mast, etc. might be expected to cause fluctuations. Atmospheric propagation can also vary from moment to moment, and this too can give rise to fluctuations in amplitude. Under circumstances such that radiation reflected from the sea surface plays a significant role in the return signal, the continually changing scattering properties of the surface will introduce amplitude fluctuations.

The question thus arises as to how RCS data is to be used for comparison of calculated and measured patterns, RCS analysis, computer model validation, and in the simulation of a radar system in order to establish its performance. Thus, it becomes obvious that statistical examination of the RCS of a target

is indispensable. A statistical examination of ship RCS offers a condensation of facts and, thus, an economy of output not available with deterministic treatment of similar scope, especially for frequencies of 1 GHz and above.

Moreover, all RCS statistics are essentially unaffected by small changes in target configuration or frequency, which may drastically affect the lobe structure of deterministic treatments. Currently I am examining various statistics, i. e. probability distribution functions, that are needed for ship RCS data analysis.

According to the previous work on this problem, ships could be represented by a random collection of scattering elements. The return would therefore evidence a Rayleigh amplitude distribution. Such a model is quite likely to be a good one for ships at some aspects, but not at others.

If the return is dominated by a single scatterer, or by only two or three scatterers, the assumptions of the Rayleigh model do not apply. This might well be the situation for bow, stern, and broadside aspects. It has been suggested that the log-normal distribution may apply for such cases.

I am also involved in RCS analysis of specific bodies of interest to the Observables Technology Division. The scattering-center concept is highly useful for analysis of radar scattering because the scattering from many types of relatively complex radar targets may be calculated by considering them to be composed of a combination of a small number of types of scattering centers.

I work in close cooperation with my research adviser Dr. Clifford R. Schumacher, Code 1411.

I have had a number of meetings with the Research Coordinator of the David Talor Naval Ship Research & Development Center Dr. David Moran, Code 012.3. During these meetings I discuss progress in my research work and future plans.

My research proposal was approved by the head of the Observables Technology Division, Dr. Charles Weller, and by our branch head, Robert H. Burns.